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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

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1 The use of multicomponent fuels in modern propulsion systems led
2 to this study of the combustion characteristics of a fuel drop containing
9 liquid constituents of different physical and chemical properties. Direct
measurements of the rate of change of cross-sectional area of a burning
drop were obtained with a photoelectric shadowgraph apparatus. The varia-
tion of burning-rate coefficient as a function of drop composition, was
determined for a group of binary fuel mixtures. In addition, the burning
characteristics of drops of hydrocarbon fuels containing up to five con-
stituents and of industrial fuel mixtures, such as kerosene and jet fuel
JP-4, were studied.

The experimental results indicate that during combustion the composi-
tion of a multicomponent fuel drop changes by a process of simple batch
distillation; that is, the vapors produced are removed continuously with-
out further contact with the residual liquid mixture. Hence, as burning
proceeds the more volatile constituents of the liquid drop vaporize first
and the concentration of the higher boiling fractions in the liquid phase
increases. Temperature and composition gradients within the burning drop
appear to be modified by internal circulation of the fuel.

For a given fuel mixture, the stability of the drop during the com-
bustion process was found to be a function of the initial drop size, the
nature and relative quantities of the components in the liquid phase,
and the magnitude of the differences in their boiling points. Motion
pictures of drops of mixtures which burn disruptively revealed the forma-
tion of bubbles which expand and burst in the liquid phase. It is sug-
gested that these effects are due to radiative heat transfer from the
flame envelope to the liquid, which results in local vaporization of the
more volatile components within the drop. It can be shown that the
radiative heat flux from the flame to the liquid is independent of drop
size; the conductive heat flux, however, is inversely proportional to
drop diameter. Thus, with decreasing drop size the latter mechanism of
heat transfer begins to make an increasing contribution. If the rates
of diffusion of mass and energy within the liquid are slow relative to
the mass burning rate, nonequilibrium distillation is to be expected.

The surface temperatures of burning drops of pure compounds were measured for (1) A drop suspended from a thermocouple junction, and (2) a fuel-wetted, porous, Alundum sphere. The values obtained from these measurements are in close agreement with those calculated on the basis of a sphericosymmetric model of a burning drop.

INTRODUCTION

During the past few years a large amount of information on the heterogeneous combustion of drops of pure fuels has been obtained (ref. 1). Liquid fuels of industrial and military importance, however, are generally composed of mixtures of chemical compounds possessing individually different physical and chemical properties. The burning characteristics of such multicomponent mixtures when dispersed as liquid aerosols have not been investigated in detail. Combustion of a binary fuel mixture over its free liquid surface produces a gradual change in the composition of the liquid phase (ref. 2); on the other hand, combustion of a fuel mixture on a wick immersed in the fluid consumes the fuel without changing its liquid composition (ref. 3). No deductions concerning the behavior of a multicomponent burning drop can be made from these observations, since in such a system the conductive heat flux increases with decreasing drop size, and the convective effects in the liquid phase are affected by the geometry.

Because of the small mass of fluid involved, it is difficult to measure the change in the chemical composition of a burning, multicomponent fuel drop. Therefore, the variation in the burning-rate coefficient ϵ was chosen as a means of examining the type of vaporization process occurring on the drop surface. This coefficient represents the slope of the curve depicting the time rate of change in cross-sectional area of the drop during combustion. For pure fuels the burning-rate coefficient remains constant (curves a and b, fig. 1) during the lifetime of the drop (ref. 1). Similarly, for a binary fuel mixture composed of compounds with individually different burning-rate coefficients, the drop cross-sectional area decreases linearly with time if the composition of the liquid phase does not vary during combustion (curve c, fig. 1). A fuel drop, however, whose constituents exhibit different burning-rate coefficients (curves e and f, fig. 1) and vaporize selectively in the manner of a batch distillation during combustion, decreases in cross-sectional area nonlinearly with respect to time (curve g, fig. 1). Consequently, measurement of the burning-rate coefficients of binary mixtures offers a suitable means of analyzing the vaporization process occurring during combustion.

The present investigation was conducted at Stanford Research Institute under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

c	specific heat at constant pressure of liquid at mean temperature between T_a and T_s , cal/g °C
c_e	specific heat at constant pressure of air at temperature T_e , cal/g °C
D	drop diameter, cm
i	stoichiometric mixture ratio, $(Y_a/Y_f)_{stoich}$
L	heat of vaporization (sensible heat plus latent heat), cal/g
m	mass burning rate of fuel, g/sec
n	total number of moles of fuel comprising drop at t_0
n'	total number of moles of fuel comprising drop at t
N	mole fraction of individual component in liquid phase of burning drop
N'	mole fraction of individual component in liquid phase of burning drop at t
N_v	mole fraction of individual component in vapor phase in equilibrium at interface of burning drop
q	heat of combustion (fuel vapor to vapor products), cal/g
R	drop radius, cm
t	time, sec
t_0	instant of ignition, sec

t_f	instant at which fuel drop is totally consumed, sec
T_a	temperature of ambient air, °K
T_c	adiabatic flame temperature, °K
T_e	log mean temperature, $\frac{T_c - T_a}{2.3 \log (T_c/T_a)}$, °K
T_s	temperature at drop surface, °K
Y_a	weight fraction of oxygen in air, 0.232
Y_f	weight fraction of fuel in vapor at interface of burning drop
ϵ	burning-rate coefficient, (diameter) ² /sec, cm ² /sec
λ_e	thermal conductivity of air at temperature T_e , cal/sec cm °C
ρ	density of liquid, g/cm ³

APPARATUS

For liquid fuel drops sufficiently small that the effect of convective heat transfer can be neglected, the mass burning rate is proportional to the drop diameter (refs. 4 and 5). Consequently, the surface area of the burning drop decreases linearly with time,

$$D^2 = \epsilon t_f \left[1 - \left(\frac{t}{t_f} \right) \right] \quad (1)$$

where the burning-rate coefficient ϵ is given by

$$\epsilon = \frac{4m}{\pi \rho D} \quad (2)$$

In this investigation, burning-rate coefficients were determined by means of a photoelectric shadowgraph apparatus which directly measures the variation of cross-sectional area of a single drop as a function of time. The device was calibrated to give the cross-sectional area of a drop in terms of the square of the diameter of an equivalent sphere. The essential features of the apparatus are illustrated in

figure 2 and are described in detail in reference 7. Fuel drops employed in the measurements had an initial diameter of the order of 1,800 microns and were burned in air at a pressure of 1 atmosphere. They were suspended from a quartz sphere approximately 800 microns in diameter which was formed on the end of a quartz fiber with a diameter of 80 microns. The drops were ignited with the flame of an alcohol burner.

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Surface temperature measurements of pure fuel drops were carried out by means of a fuel-wetted porous sphere, which has previously been described (ref. 5). The device was modified as shown in figure 3. A surface temperature measurement was made by adjusting the fuel-feed rate to the sphere to exceed the mass burning rate of the system, thus establishing a surplus of liquid at the sphere surface. This surplus coalesced in a pendent mass of fluid which completely enveloped the thermocouple junction (Chromel-Alumel, 3-mil wires). When the fuel-feed rate was decreased to a value less than the characteristic mass burning rate, the mass of pendent fluid diminished, and its receding lower surface advanced toward the junction. The moment the thermocouple junction pierced the film of liquid it crossed a large temperature gradient, and the slope of the thermocouple output curve traced by a recording potentiometer increased sharply. The temperature indicated at this departure was taken as the surface temperature of the burning drop.

Additional surface temperature measurements were made by burning small drops of fuels suspended from the junction of a thermocouple. The thermocouple wires were insulated from the hot zone of the flame by a noncatalytic ceramic coating, National Bureau of Standards ceramic coating A-418 obtained from California Metal Enameling Co. The thermocouple junction was situated about 1 millimeter below a ceramic bead fused to the wires, which served as a supporting surface for the liquid drop. A drop suspended from this fixture assumes a lemon shape, for the pressure of the thermocouple junction against the surface causes a slight protuberance. The liquid-vapor interface remains integral, however, during the burning lifetime of the drop; the thermocouple junction pierces the surface only at the moment the drop is totally consumed. The temperature, displayed as a function of time on an oscilloscope, gradually rises to a steady value which is terminated by a sudden, sharp increase (fig. 4). The initial rise obviously represents the warming-up of the drop and possibly its support, while the final spurt marks the penetration of the drop surface by the thermocouple junction; the temperature indicated by the level portion of the curve was selected as the value of the surface temperature.

EXPERIMENTAL RESULTS

The three binary fuel mixtures studied in this investigation were: (1) Heptane and butanol-1, (2) 2,2,4-trimethylpentane and butanol-1, and (3) dibutyl ether and pentanol-1. The alcohols were analytical reagents used without further purification; the hydrocarbons were obtained from Phillips Petroleum Co., and were rated at 99⁺-percent purity; the dibutyl ether was Eastman practical grade. Mixtures of various proportions of these liquids were prepared by volumetric dispensation of the components from burettes.

In figure 5 the drop burning characteristics of binary mixtures are compared with those of their pure constituents. The pure fuel drops exhibit linear changes of cross-sectional area with time, that is, their burning-rate coefficients remain constant during the drop lifetime. On the other hand, the burning-rate curve produced by the fuel mixture containing equimolar quantities of butanol and heptane, for example, exhibits curvature. At the beginning of combustion the slope approaches that of the azeotropic composition (25 mol-percent butanol), while near the end, that of pure butanol. The initial and final values of the burning-rate coefficients of the various fuel mixtures are summarized in figure 6. The results indicate that the composition of the liquid phase changes during combustion in a manner which can be described as a batch distillation process, in which the liquid and the vapor are in equilibrium with respect to composition and temperature, rather than nonequilibrium distillation (see calculated values indicated in figure 6). For mixtures which contain a relatively small mole fraction of their more volatile components, the experimental data suggest constant burning rates. This effect is probably due in part to the loss of the volatile component from the liquid phase preceding ignition of the drop and to the ignition process.

The drop burning characteristics of mixtures of a number of aliphatic hydrocarbons with carbon chains varying between seven and sixteen atoms in length were observed. A number of these mixtures exhibited an unsteadiness during combustion which is termed disruptive combustion (table I). Visually, the phenomenon appears as a sudden oscillation of the drop on its supporting fiber, accompanied by ejection of small quantities of liquid fuel in random directions. The manner in which disruptive combustion affects the burning curve is demonstrated in the oscilloscope record in figure 7.

The measured surface temperatures of burning drops are summarized in table II. There is good agreement between the data obtained by the two experimental methods.

DISCUSSION

Combustion of a Multicomponent Fuel Drop

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The burning rate of a small liquid fuel drop in an oxidizing atmosphere is controlled by the transport of mass and energy. Consequently it is a function of the thermodynamic properties of the fuel-oxidizer system and the transport properties of the gaseous envelope surrounding the drop. Since these parameters are characteristics of the chemical composition of a fuel, it is evident that the burning rate of any mixture of miscible compounds depends upon the nature and proportions of the constituents.

There are two basic mechanisms by which fuel can vaporize from the surface of a burning drop made up of a multicomponent solution. First, the vapors leaving the surface may have a composition identical to that of the liquid phase, as shown schematically in figure 8, line A. Under such conditions of nonequilibrium distillation, the burning characteristics of a binary fuel mixture resemble those of a pure fuel, for there occurs no change of composition during the lifetime of the drop.

Secondly, a thermodynamic equilibrium may be established at the interface between liquid and vapor so that the components vaporize from the burning drop in continuously varying composition ratios, each of which is uniquely determined by the instantaneous temperature of the liquid phase (fig. 8, line B). It is conceivable also that the vaporization process may occur in a manner intermediate between these two cases, producing an unpredictable variation in the composition of the unburned portion of the drop (fig. 8, line C). These processes assume a uniform composition within the liquid at every instant, such as could be produced by convective mixing within the drop. It has been found by El Wakil and co-workers (ref. 8) that the fluid within a drop evaporating in a heated airstream circulates rapidly enough to eliminate temperature gradients in the liquid. Similar observations, which demonstrated circulation within the liquid of a burning drop, were made during this investigation.

For a burning-drop model in which a spherical flame envelope is maintained around the liquid sphere, heat- and mass-transfer considerations lead to an expression of the burning-rate coefficient in terms of thermodynamic properties of the drop and transport properties of the gas film between drop and flame. Since the gaseous region between the fuel and the reaction zone of a diffusion flame has been shown to consist predominantly of nitrogen, carbon dioxide, and water vapor for a number of representative organic fuels (ref. 9, pp. 759 and 1059), the transport properties of the gaseous envelope around a burning drop may be considered independent of liquid composition within the category of ordinary

organic fuels. In addition, it was noted that the quotient of heat of combustion and stoichiometric mixture ratio (q/i) for the fuels employed in this investigation is essentially a constant (table III). At any instant during the combustion process the theoretical burning-rate coefficient for the binary mixture is:

$$\epsilon_{1,2} = \frac{8\lambda_e}{(Y_1\rho_1 + Y_2\rho_2)c_e} \log_e \left\{ 1 + \frac{1}{(Y_1L_1 + Y_2L_2)} \left[\frac{Y_a q}{i} - c_e(T_s - T_a) \right] \right\} \quad (3)$$

Burning-rate coefficients for drops of the pure constituents of the mixtures were calculated from this equation, using the numerical values given in table III. The adiabatic flame temperatures of these fuels are nearly identical; so for all cases λ_e and c_e were evaluated for air at the logarithmic mean temperature between T_c and T_a (ref. 6).

An examination of the burning curves in figures 5(a) and 5(b) shows that fuel mixtures in the center of the composition range display time variations in their burning rates. A theoretical analysis was attempted, based on the assumption that the composition of the drop at any time during the burning lifetime could be characterized from the equilibrium distillation curves for the appropriate system. Such an assumption requires that (1) The ignition lag of the drop be small, so that the liquid-vapor interface rapidly attains thermodynamic equilibrium with its immediate surroundings, and (2) the temperature of the interface be sufficiently close to the normal boiling point of the system (cf. table II) to permit composition to be estimated from ordinary distillation curves for 1 atmosphere pressure.

The burning curves obtained from drops of pure organic compounds and binary azeotropes give an indication of the ignition lag. The instant of ignition of the drops is indicated in figure 5 by the arrows, with an estimated precision of ± 0.1 second. The shoulder of each curve immediately follows ignition and spans the period of time during which the burning rate of the drop rises to its characteristic steady-state value. In all cases, the length of this span represents approximately 15 percent of the total burning lifetime of the drop.

In accord with theoretical calculations, experimental measurements on burning drops of the pure compounds used in this investigation demonstrated that the surface temperatures are below the normal boiling points of the fuels (table II). Consequently, the estimation of the time variation of composition of a drop on the basis of ordinary distillation curves can be regarded only as a first approximation.

The distillation curves for the three systems of interest were determined in this laboratory. Since liquid-vapor equilibrium data for

these binary mixtures are not presently available in the literature, the phase diagrams and the techniques employed in their determination are presented in the appendix.

The Rayleigh equation

$$\log_e \frac{n'}{n} = \int_N^{N'} \frac{dN}{(N_V - N)} \quad (4)$$

relates the composition of a residue in a simple batch distillation to the mole fraction of the original distilland remaining at any given instant (ref. 10). The value of the integral between various arbitrarily selected limits of liquid composition (N to N') was determined graphically by summing the area under the plot of N versus $1/(N_V - N)$, the points for which were obtained from the distillation curves. The results of this integration were a series of composition values corresponding to mole fractions of the liquid drop yet unburned. The unburned mole fraction of fuel is a function of the cross-sectional area of the drop. By assuming an average molecular weight for the fuel mixture, the composition of the liquid phase as a function of time after ignition may be explicitly calculated from the experimental burning-rate curves. Sets of composition values were obtained, therefore, corresponding to periods of time elapsed after ignition for specific burning drops of binary fuels. Examples of these results, which illustrate the rapidity with which certain mixtures change composition, are presented in table IV. It is to be noted that the mixture with an initial composition of 10 percent butanol approaches pure 2,2,4-trimethylpentane as it burns, while the other mixtures approach pure butanol. This is caused by the existence of an azeotrope with a minimum boiling point at a composition of 17.5 percent butanol.

By introducing the composition values thus obtained into equation (3), the instantaneous burning-rate coefficients for burning drops of binary mixtures of interest were calculated. These values are presented in the form of theoretical burning-rate curves in figure 9. Superimposed on the theoretical curves are points taken from the burning-rate measurements of drops of identical initial composition. In view of the approximations made in selecting the vapor film properties, the degree of agreement is satisfactory. One may conclude that after a brief ignition lag a simple equilibrium batch distillation is an adequate description of the vaporization process which a two-component drop undergoes during combustion.

In the light of these experiments it is not surprising that the burning curves for drops of many multicomponent fuels of practical importance are quite linear. The explanation lies in the fact that the thermodynamic characteristics of all the components are such that the

individual burning-rate coefficients vary over a narrow range. The pentanol-dibutyl ether system, figures 5(c) and 9(c), displays this property for the case of a binary fuel mixture; the practical fuels, kerosene and jet fuel JP-4 (fig. 10), exhibit this characteristic for multicomponent mixtures.

Disruptive Drop Combustion

By photographing burning drops with a motion-picture camera, the phenomenon of disruptive combustion was shown to be associated with the formation of minute bubbles or vapor pockets in the liquid phase. The photographs of figure 11 are successive frames from a motion-picture film which reveal the formation and disintegration of such a disturbance. Frame I shows the quietly burning drop 1.149 seconds after ignition; the dark spots are highlights produced by the strong side illumination of the drop. The beginning of a bubble is visible in the upper right quadrant of the drop in frame II, and the subsequent growth of the disturbance can be followed in frames III through V. The bubble apparently burst before frame VI was exposed, and within the time elapsed during the next two frames, the drop returned to quiescent combustion. The burning curve (fig. 7) for the same drop photographed in this sequence clearly shows the disruptions. In this case, a small loss of material from the liquid phase had a negligible effect on the characteristic burning rate.

It is probable that this phenomenon is associated with the transfer of radiant energy from the flame into the interior of the drop. Calculations of temperature profiles have indicated that under conditions of absorption of incident radiant energy the temperature inside a drop can exceed that on the surface (ref. 11). The contribution of radiative heat transfer to a burning drop was demonstrated experimentally by enhancing the absorptivity of the fuel. Unfortunately, compounds such as acetonitrile and phenylacetonitrile, which absorb in the spectral region in which hydrocarbon flames emit strongly (~ 4.5 microns), are quite insoluble in fuels such as those employed in this investigation. The addition of a particulate black dye which forms a slurry appeared to be the only way to change the absorptivity of the hydrocarbon fuel drops significantly (ref. 12). To magnify the effect which a change in fuel absorptivity would produce in a burning drop, a fuel mixture was selected which burned quietly but which possessed a wide boiling range and therefore a susceptibility to disruptive combustion (cf. table I). Small quantities of Apiezon W black wax were added to a 50-50-volume-percent mixture of nonane and tetradecane. Microscopic examination of the filtered solution, which was brown in color, indicated that the coloring matter existed in the form of a particulate suspension within the drop. Absorption spectrograms of the colored solution showed a very small, uniform increase in optical density over the clear fuel in

the region of 4 to 5 microns. Nevertheless, drops of the colored solution burned disruptively. To preclude the possible explanation that the particulate material within the drop provided nuclei for bubble formation, a parallel experiment was carried out in which finely ground alumina was dispersed in the fuel. The addition of these white reflective particles had no effect on quiescent combustion of the nonane-tetradecane mixture.

It appears, therefore, that radiant energy transfer to a liquid drop may result in the formation of a local hot zone within the liquid phase. If the drop is composed of fuels which boil over a sufficiently large temperature range and which are blended in a suitable quantitative ratio, this hot zone will cause the lower-boiling constituents to vaporize rapidly and disrupt the liquid-vapor interface. Apparently, internal circulation is not sufficient to eliminate these inhomogeneities caused by radiant heat transfer. Also, it is to be noted that, although radiative heat flux is independent of drop size, conductive heat flux from the flame to the liquid increases with decreasing drop diameter. Thus, the process of batch distillation observed in the present measurements may change to one of nonequilibrium vaporization for drops much smaller than those employed in these studies. Under these conditions, the rates of convective transfer of mass and energy within the liquid phase may be slow relative to the mass-burning rate. The diminished role of radiative heat transfer in small drops would decrease the likelihood of disruptive burning; but the diminution of convective heat and mass transfer within the liquid phase would augment the tendency of a drop to burn disruptively as a result of increased conductive heat flux. Hence the dependence of disruptive combustion on drop diameter cannot be predicted quantitatively.

An estimate of the disruptibility of fuel drops in a combustion chamber should not be based entirely on the burning characteristics of single drops, for, in practice, a major portion of the radiant heat seen by a drop arises from the hot walls of the chamber. The spectral characteristics of such hot-wall radiation are quite different from the energy spectrum of a flame.

Surface Temperature of Drop

Calculations of the drop surface temperature are based on the burning-rate equations derived for the spherically symmetric model of a burning drop. The weight fraction of fuel vapor at the surface of the drop is given by the following equation (ref. 13):

$$Y_f = 1 - \left\{ \left(1 + \frac{Y_a}{i} \right) / \left[1 + \frac{qY_a}{Li} + \frac{c(T_a - T_s)}{L} \right] \right\} \quad (5)$$

In using this equation for the computation of T_s , an iterative procedure was employed. First, the assumption was made that the temperature T_s was the normal boiling point of the fuel, and the weight fraction of fuel vapor at the interface Y_f was calculated. For this value of Y_f the equilibrium temperature T_s was obtained from vapor pressure data and substituted again into equation (5) as the next approximation in the iteration. Rapid convergence of the results was noted; for most of the fuels two repetitions produced a constant value of Y_f . As in the calculation of the theoretical burning-rate coefficients, mean values of the transport parameters were used.

The results are presented in table II together with the experimental values obtained. In general, there is good agreement.

Stanford Research Institute,
Menlo Park, Calif., January 15, 1958.

APPENDIX

DETERMINATION OF DISTILLATION CURVES FOR
BINARY FUEL MIXTURES

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9. The compositions of liquid and vapor in thermodynamic equilibrium at the normal boiling points of the binary fuel mixtures employed in this investigation were determined with the apparatus of Daniels et al., reference 14 (fig. 12). A distilland of known composition was placed in the flask by dispensing known volumes of the constituents from burettes. The fluid was brought to a boil and allowed to reflux until a steady boiling point was established. The apparatus was then allowed to cool, and the reflux residue, which represented at most 1 percent of the total liquid volume of the system, was removed with a pipette and analyzed.

The temperature of the boiling distilland was measured with a precision of $\pm 0.1^{\circ}$ C with an ASTM aniline point thermometer (51-millimeter immersion; range, 90° - 170° C). The pressure of the atmosphere varied between 756 and 760 millimeters of mercury during the course of the experiments.

Reflux residues from the heptane-butanol and the 2,2,4-trimethylpentane-butanol systems were analyzed by determining the refractive indices of samples with an Abbé refractometer. Analyses of the dibutyl ether-pentanol system were made by means of vapor-phase chromatography. Samples of the condensed vapor were introduced into a column containing a silicone oil adsorbent maintained at 150° C. The constituents were separated cleanly in the column, and their relative proportions in the efflux were determined with a thermal conductivity cell which had been previously calibrated with known mixtures of the compounds. The resulting distillation curves are presented in figure 13.

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TABLE I
BURNING CHARACTERISTICS OF DROPS OF MIXED FUELS^a

Mixtures	Boiling point of constituents, °C	Character of combustion process	Increment between boiling points of terminal constituents, °C
Heptane Nonane	98.4 151	Quiet	52.6
Heptane Tetradecane	98.4 253	Disruptive	154.6
Heptane Hexadecane	98.4 288	Disruptive	189.6
Heptane Nonane Tetradecane	98.4 151 253	Disruptive	154.6
Heptane Octane Nonane Tetradecane	98.4 126 151 253	Disruptive	154.6
Nonane Tetradecane	151 253	Quiet	102
Nonane Hexadecane	151 288	Disruptive	137
Nonane Tetradecane Hexadecane	151 253 288	Quiet	137
Heptane Nonane Tetradecane Hexadecane	98.4 151 253 288	Disruptive	189.6
Heptane Octane Nonane Tetradecane Hexadecane	98.4 126 151 253 288	Disruptive	189.6

^aLiquid solution was made up of equal volumes of each constituent.

TABLE II

SURFACE TEMPERATURES OF BURNING LIQUID DROPS

Fuel	Boiling point, °C	Surface temperature, °C		
		Theoretical, (ref. 13)	Porous sphere experiment	Hanging drop experiment
Ethanol	78.4	68	72.5	72
Butanol-1	118	101	108	105
Pentanol-1	138.1	117	124	125
Octanol-1	194.5	161	163	171
2,2'-Oxydiethanol	244	211	215	226
Heptane	98.4	84	84	82
Octane	125.7	---	108	104
Kerosene	^a 225	^b 185	202	---

^aMean boiling point.

^bCalculated on basis of a pure hydrocarbon with boiling point of 225° C.

TABLE III
PROPERTIES OF FUELS USED IN CALCULATION OF
BURNING-RATE COEFFICIENT

[Transport properties of vapor film were taken as those of air at logarithmic mean temperature between flame and ambient temperature (cf. pp. 1 and 6, ref. 6): $C_e = 0.271 \text{ cal/gm } ^\circ\text{C}$; $\lambda_e = 1.56 \times 10^{-4} \text{ cal/sec cm } ^\circ\text{C}$. Since drops were burned in air at 1 atmosphere, $Y_a = 0.232$.]

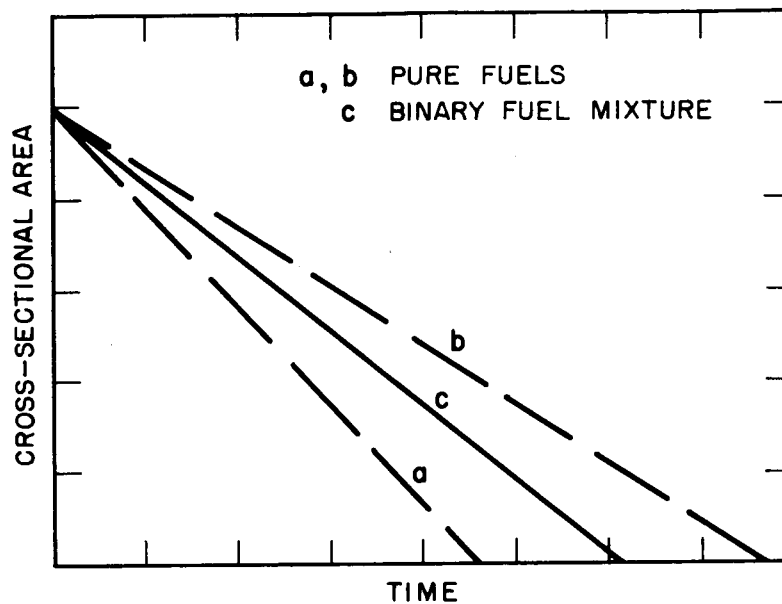
Fuel	ρ , gm/cm ³	L , cal/gm $^\circ\text{C}$	q , cal/gm	i , gm/gm	q/i , cal/gm	bp, $^\circ\text{C}$
Butanol-1	0.810	207.0	8,051	2.59	3,110	118
Heptane	0.684	121.6	10,720	3.51	3,060	98
2,2,4-Trimethylpentane	0.692	106.8	10,672	3.51	3,040	99
Pentanol-1	0.818	201	8,420	2.72	3,100	138
Dibutyl ether	0.773	185	8,850	2.87	3,080	142

TABLE IV
COMPOSITION VARIATION OF BINARY FUEL DROPS DURING COMBUSTION

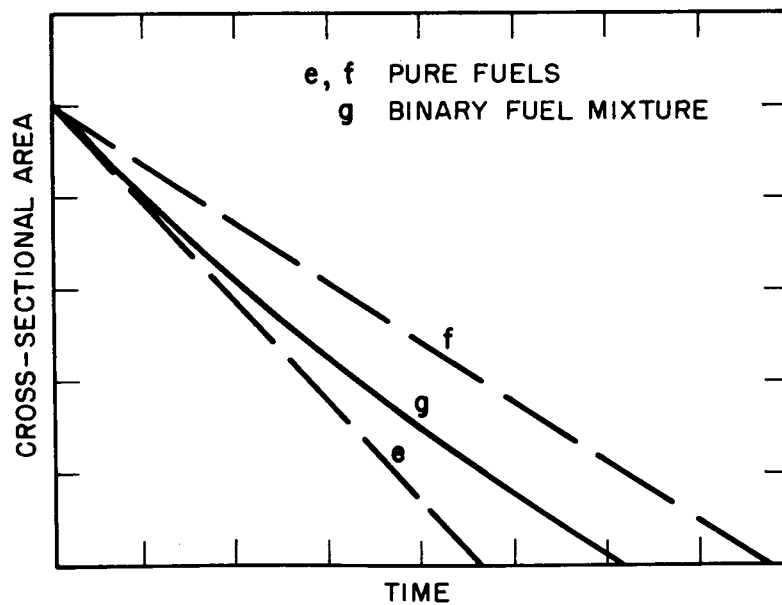
SYSTEM: 2,2,4-TRIMETHYLPENTANE-BUTANOL-1

Elapsed time after ignition, sec	Composition, mol percent Butanol-1	Initial drop diameter, cm
0 .5 1.0 1.5 2.0 2.5 2.6	10 8.5 6.0 3.5 2.0 0 0	16.2×10^{-2}
0 .5 1.0 1.5 2.0 2.5 2.75	40 46 58 70 100 100 100	
0 .5 1.0 1.5 2.0 2.5 3.0 3.2	50 55 65 88 100 100 100 100	15.6×10^{-2}
0 .5 1.0 1.5 2.0 2.5 3.0	60 66 83 100 100 100 100	
0 .5 1.0 1.5 2.0 2.5 3.0 3.5 3.75	75 81 91 100 100 100 100 100 100	16.1×10^{-2}

W
1
2
9



(a) Nonequilibrium distillation.



(b) Equilibrium distillation.

Figure 1.- Schematic presentation of variation of drop cross-sectional area with time during combustion.

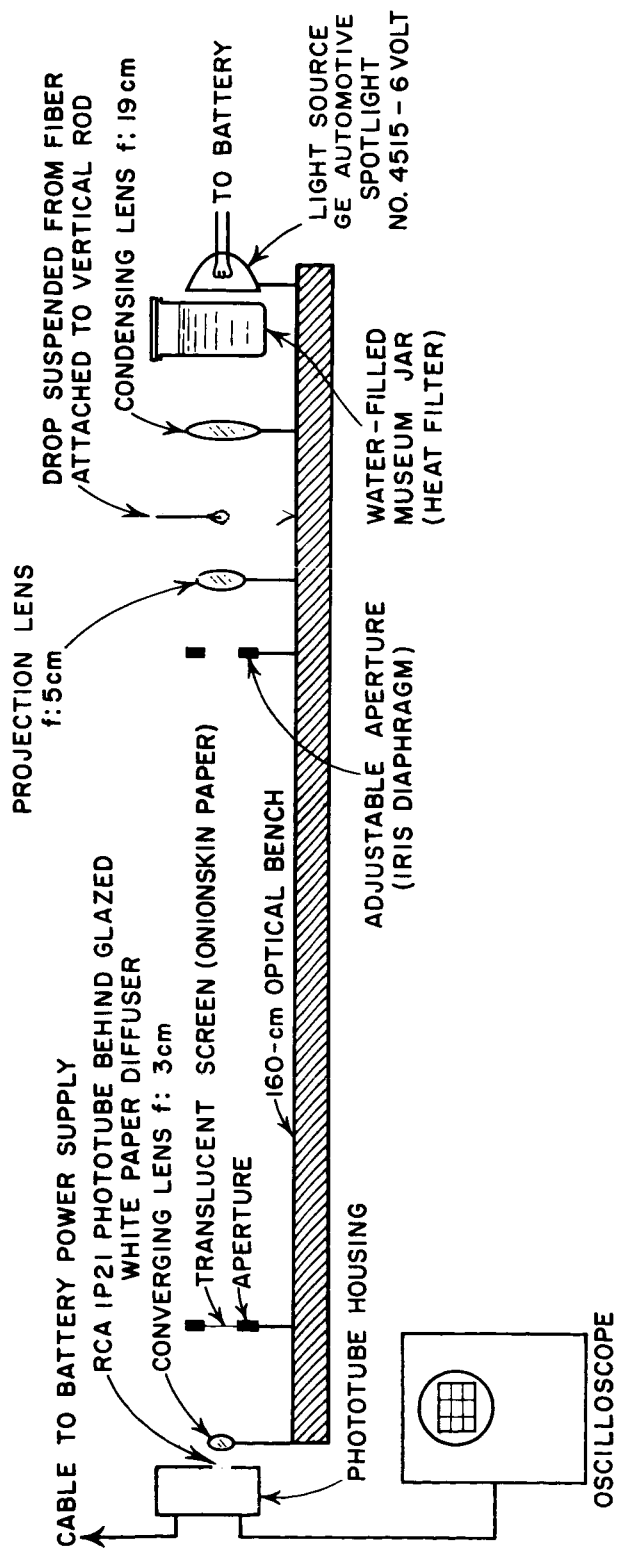


Figure 2.- Schematic diagram of photoelectric shadowgraph apparatus.

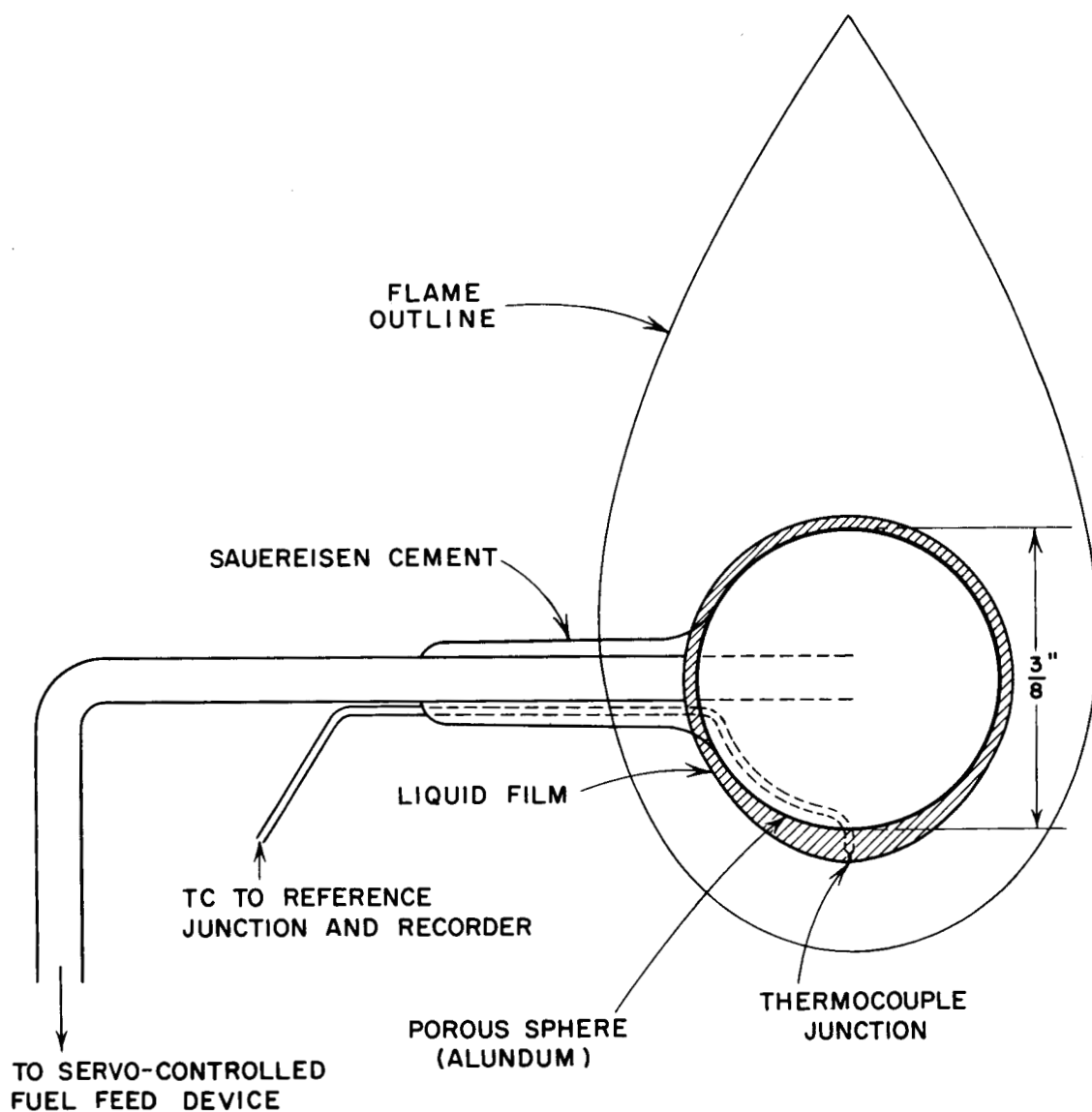


Figure 3.- Schematic diagram of fuel-wetted porous sphere with thermocouple for measurement of liquid surface temperatures.

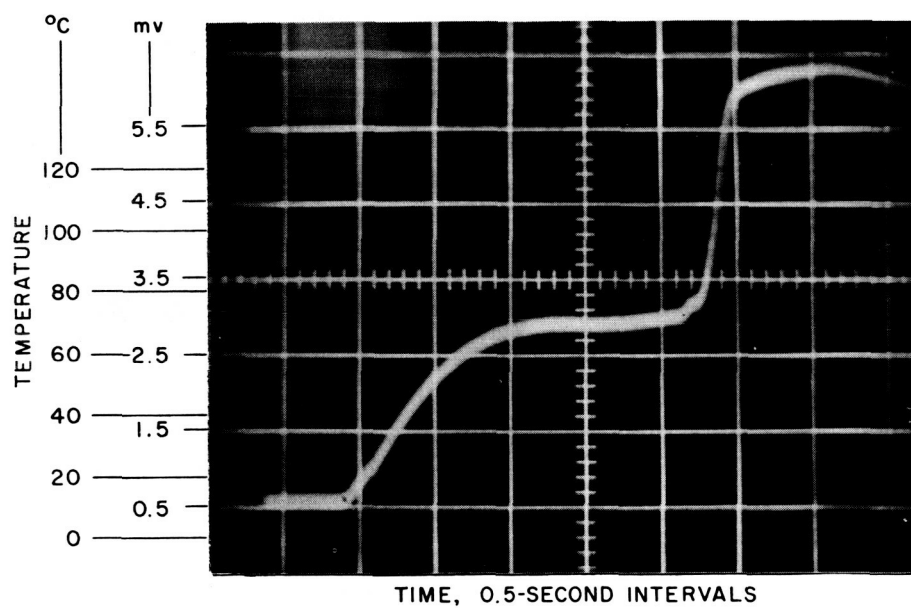
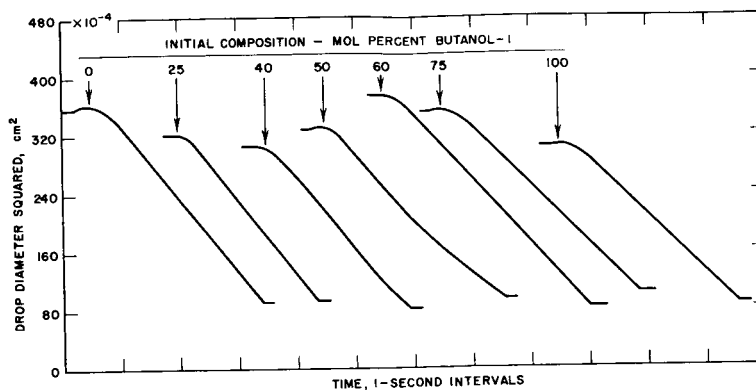
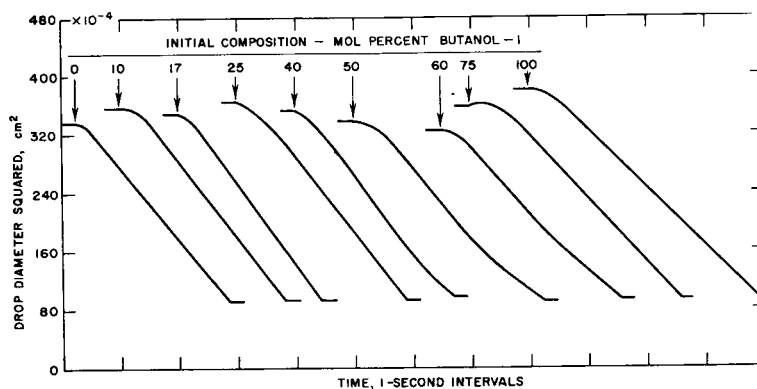


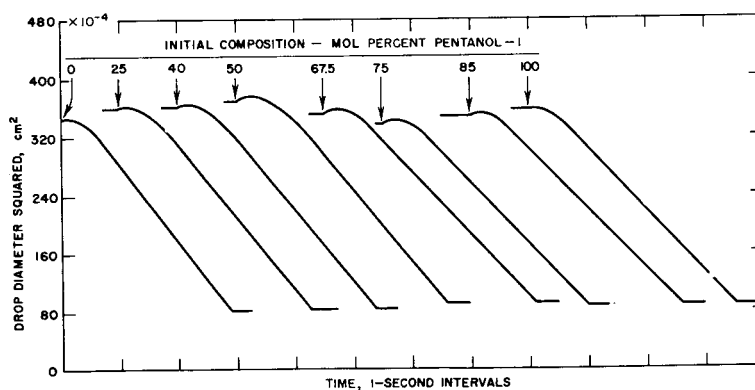
Figure 4.- Time-temperature record associated with burning of suspended ethanol fuel drop.



(a) Butanol-1 and heptane.

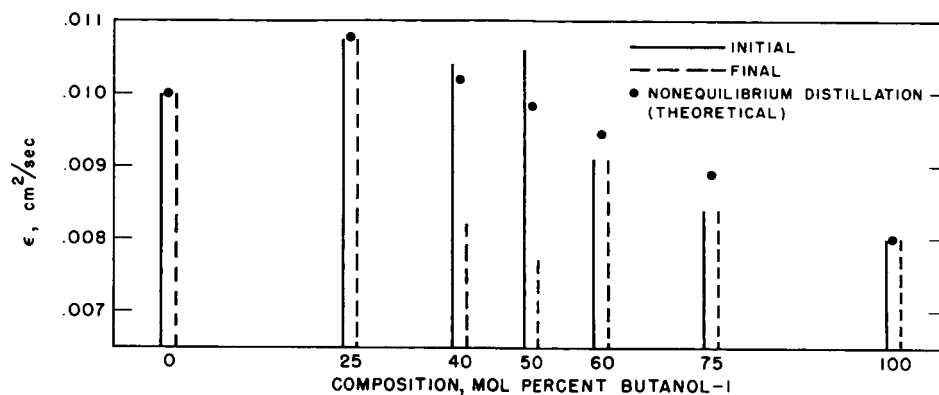


(b) Butanol-1 and 2,2,4-trimethylpentane.

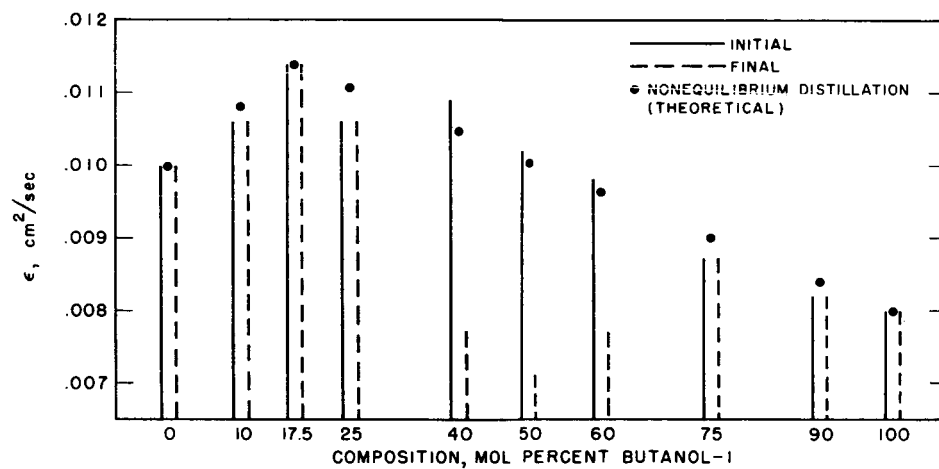


(c) Pentanol-1 and dibutyl ether.

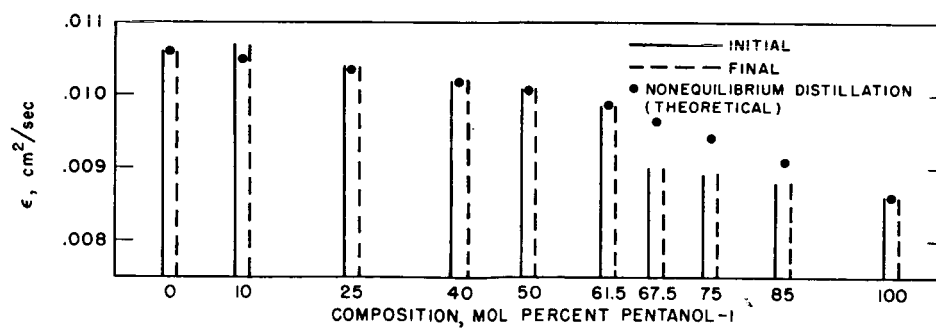
Figure 5.- Burning-rate curves for various binary fuel mixtures.



(a) Heptane-butanol-1.



(b) 2,2,4-trimethylpentane-butanol-1.



(c) Dibutyl ether-pentanol-1.

Figure 6.- Burning-rate coefficients for various binary fuel mixtures.

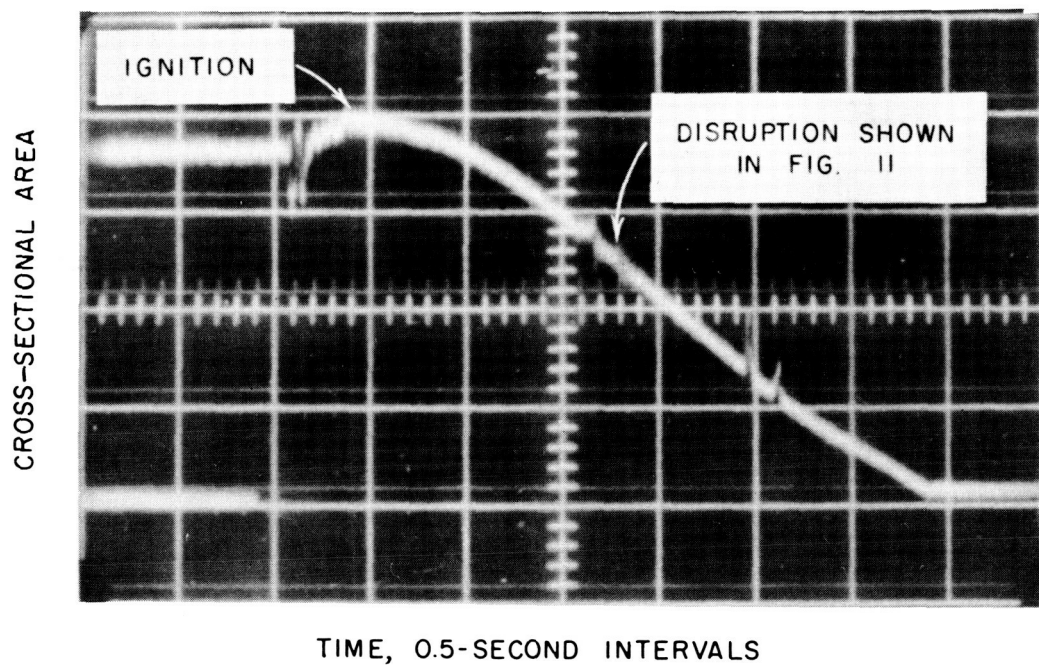


Figure 7.- Burning-rate curve for binary fuel showing disruptive combustion. (Fuel: 50-50 mol percent heptane-hexadecane, Cf. fig. 11.)

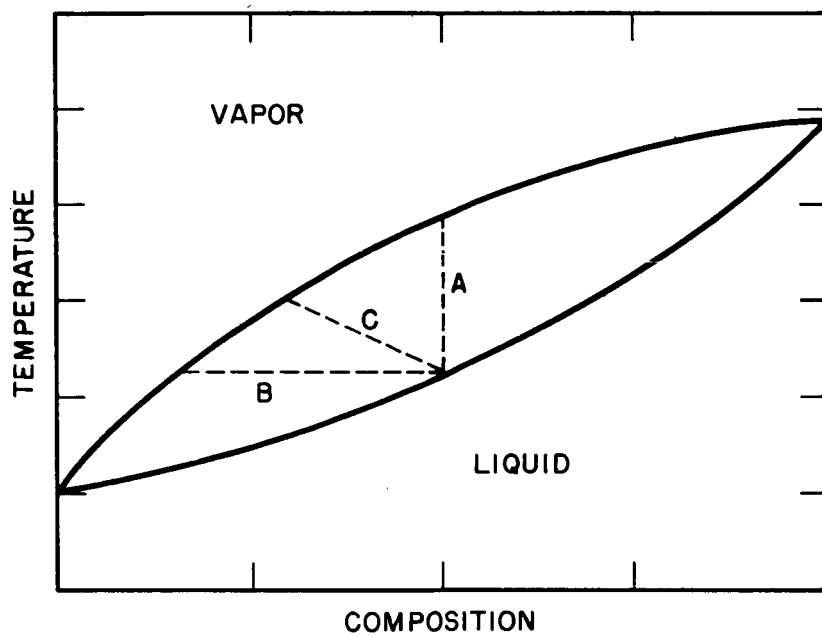
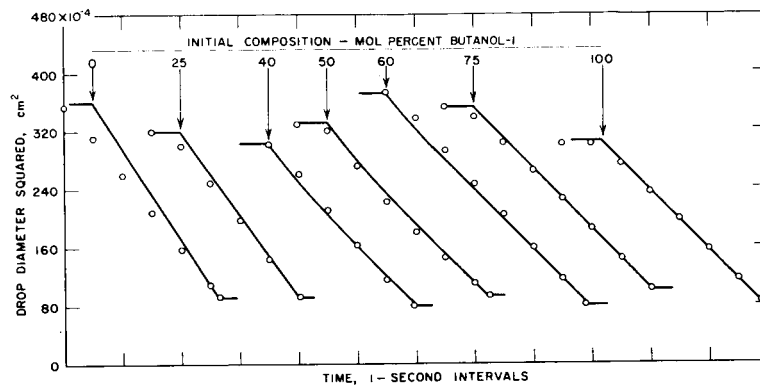
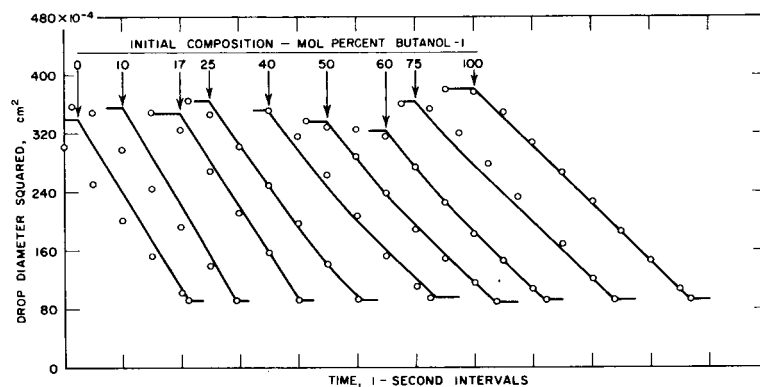


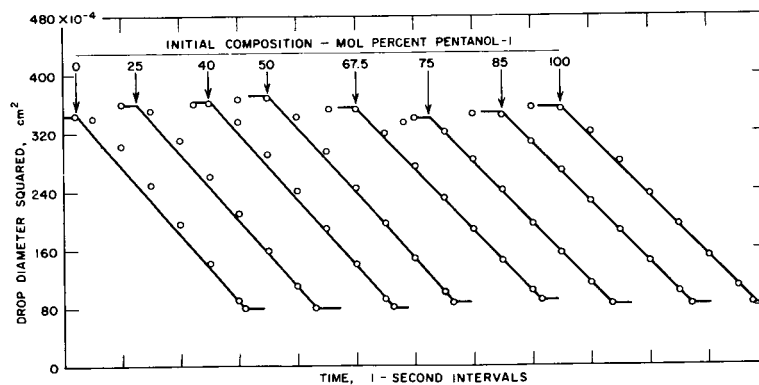
Figure 8.- Schematic presentation of vaporization of binary fuel drop during combustion. Nonequilibrium distillation, A, C; equilibrium distillation, B.



(a) Butanol-1 and heptane.



(b) Butanol-1 and 2,2,4-trimethylpentane.



(c) Pentanol-1 and Dibutyl ether.

Figure 9.- Theoretical burning-rate curves for various mixtures.
Circles indicate experimental points.

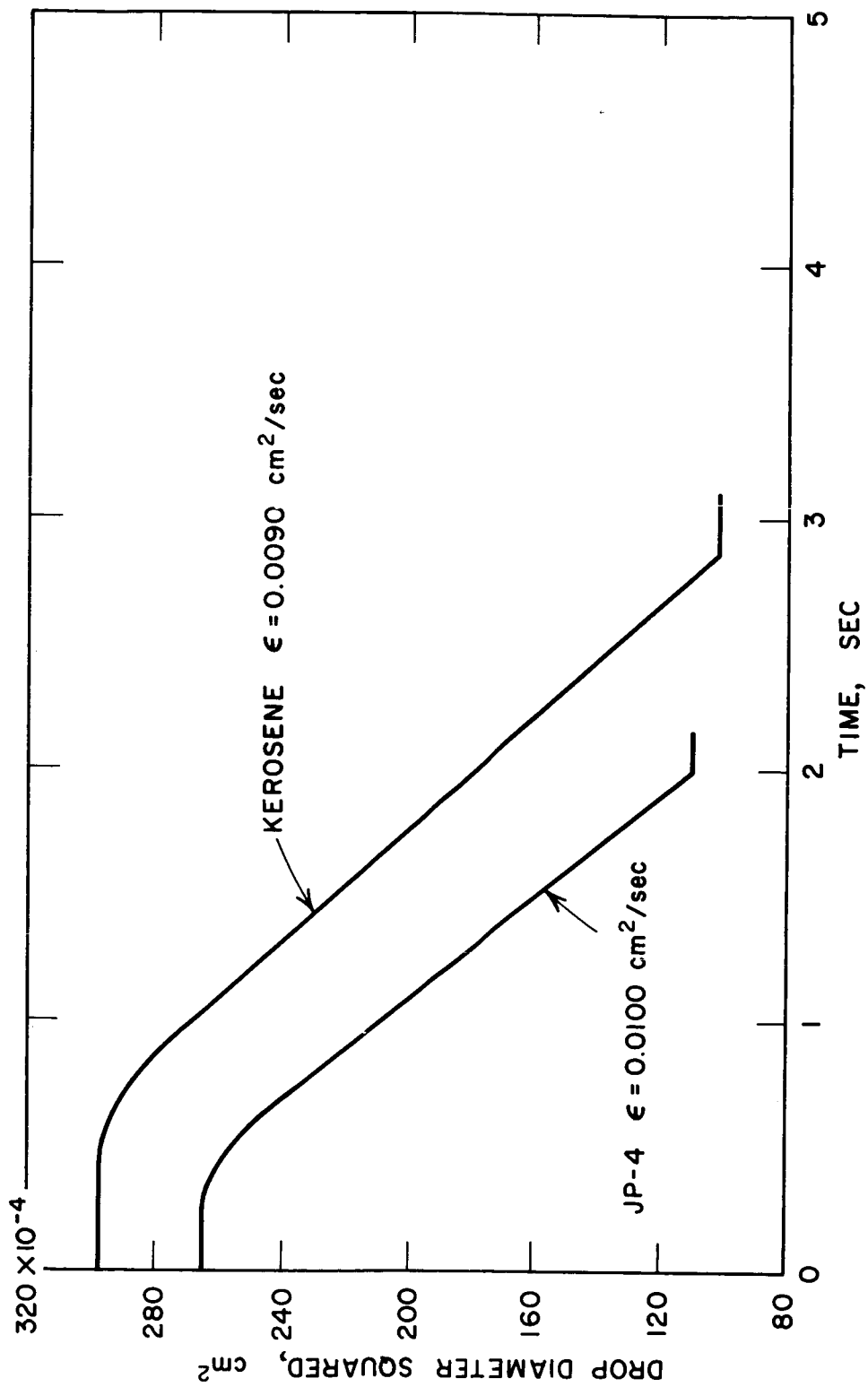
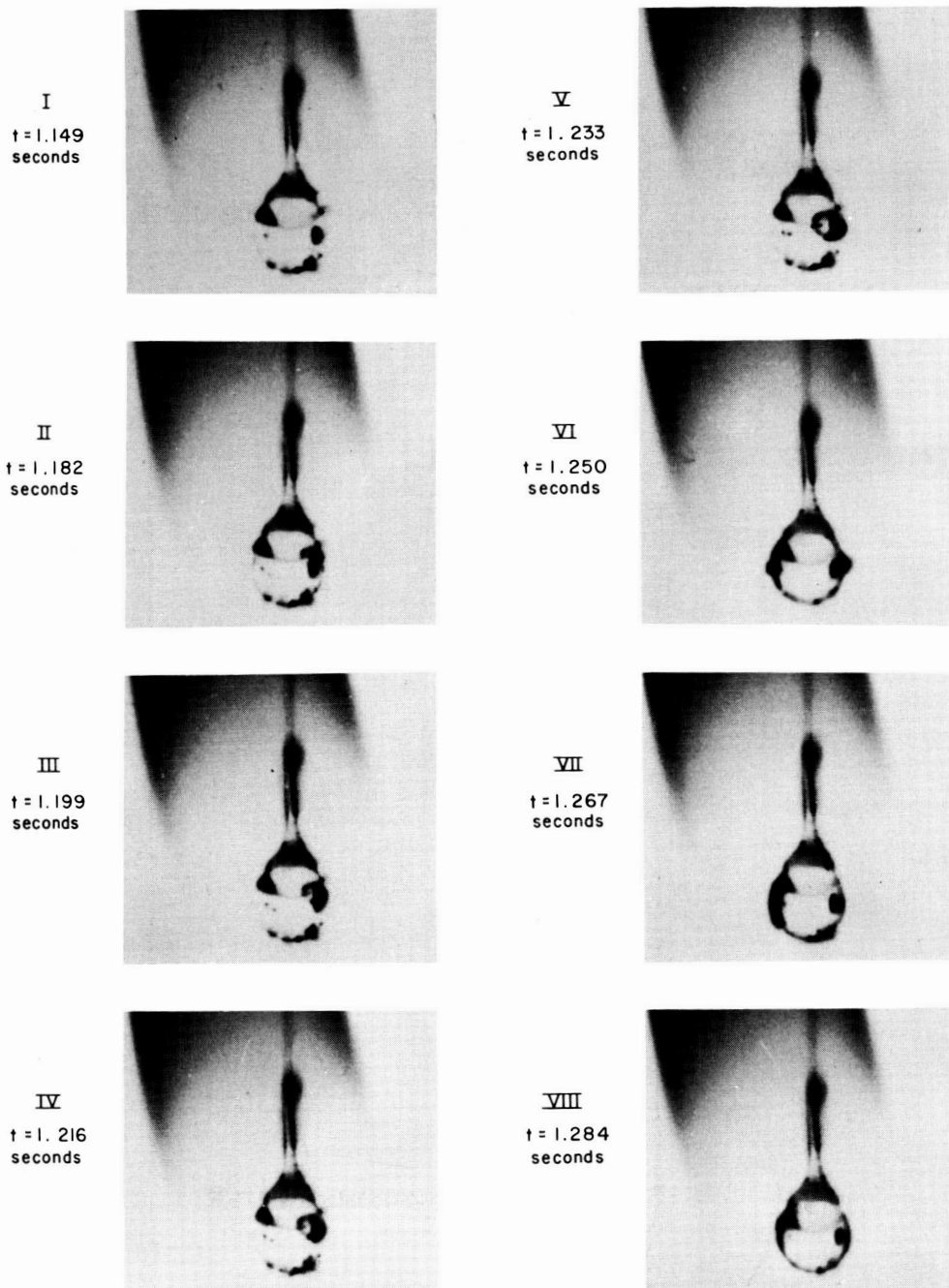


Figure 10.- Burning-rate curves for kerosene and jet fuel JP-4.



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Figure 11.- Formation of bubble in liquid phase of burning drop. (Fuel: 50-50 mol percent heptane-hexadecane; diameter of supporting fiber tip: 1,000 microns; t indicates elapsed time after ignition; burning-rate curve produced by this drop is presented in fig. 7.)

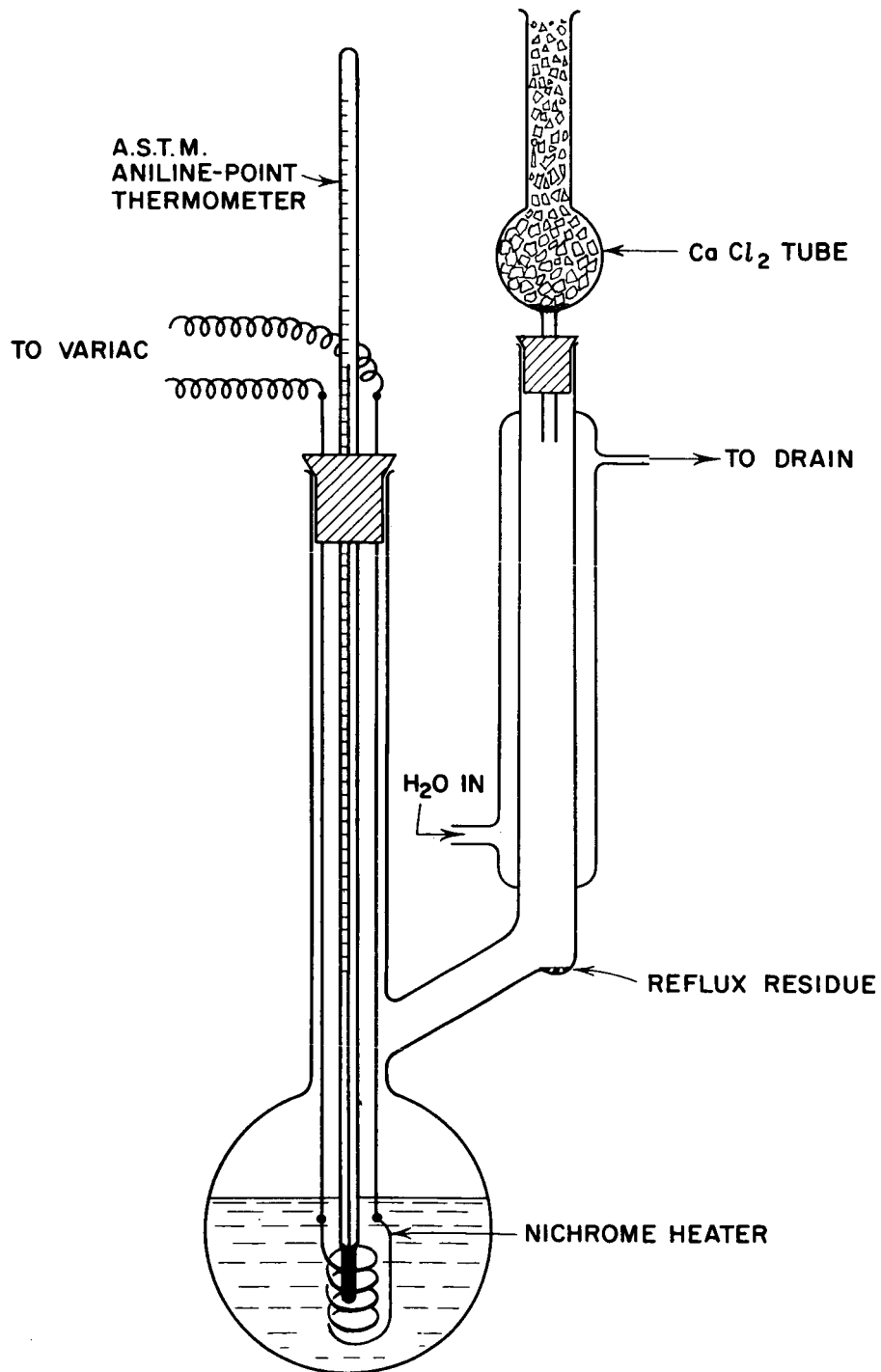
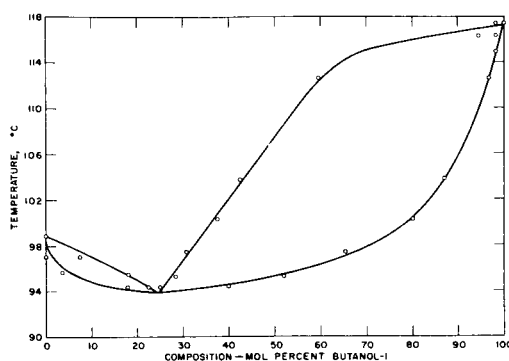
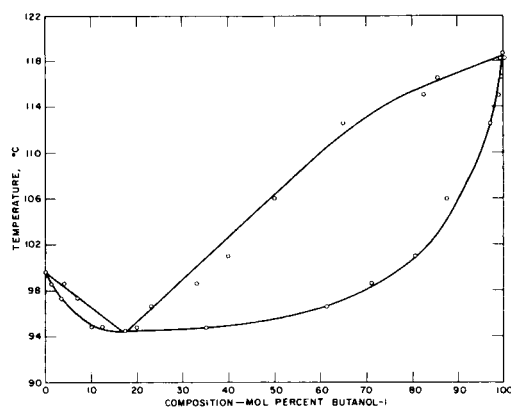


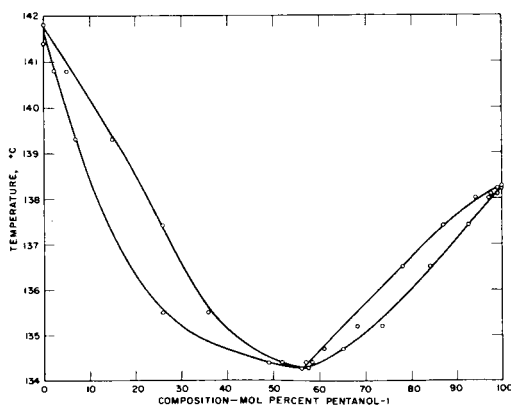
Figure 12.- Apparatus for determination of boiling points and liquid-vapor compositions of binary solutions.



(a) Heptane-butanol-1.



(b) 2,2,4-trimethylpentane-butanol-1.



(c) Dibutyl ether-pentanol-1.

Figure 13.- Liquid-vapor equilibrium composition as a function of temperature at a pressure of 1 atmosphere.